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Research papers

Can antecedent moisture conditions modulate the increase in flood risk due to climate change in urban catchments?

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ABSTRACT

Climate change coupled with the current trend in rapid urbanization is increasing the risk of flooding that can cause loss of life and damage to property. Adapting to climate change impacts and flood mitigation has become a life critical factor as well as a severe challenge. Green infrastructure and low impact development methods are common approaches that are increasingly used to address stormwater management in developed environments. The analysis and results of this study show that AMC/IC does impact flood response even in urban developed catchments and that it can significantly impact flood responses during storm events. We show that considering AMC/ICs coupled with changes in seasonal rainfall patterns that are projected for warmer climates in the future can modulate some of the increases in flood risk due to climate change.

The prevailing thought is that Antecedent Moisture Conditions (AMCs) have little to no relevance in urban hydrology, particularly in relation to climate change. However, current trends in use of stormwater management methods that depend on local storage and infiltration is increasingly making AMC or Initial Conditions (IC) a factor in urban flooding. Despite this trend there is little available literature that discuss the aspect of AMC/IC that can have an implication on urban flood management. Here, we move towards filling this gap in current literature related to impacts of AMCs in flooding of developed areas by focusing on how possible changes in seasonal rainfall patterns in a warming climate might impact AMC and starting conditions in stormwater Best Management Practices (SWBMPs), and how those changed initial conditions impact flood risk in developed areas. Using a comprehensive hydrologic/hydraulic model of an urban/developed catchment and continuous simulation, we demonstrate the importance of accurately accounting for initial conditions in flood assessments. We consider average summer temperatures based on approximately 70 years of historic data to select warm and cold years. We compare the model results between the warm and cold years as a proxy to look at trends related to a future warming climate.

1. Introduction

The current trend in population demographics and rapid urbanization is increasing the risk of flooding that can cause loss of life and damage to property. The risks of urban flooding and related stresses are exacerbated by climatic changes that are projected to occur (Ashley et al., 2005; Miller and Hutchins, 2017; Schreider et al., 2000; Willems et al., 2012b; Zhou et al., 2016). Warming temperatures are projected to intensify storms in a future climate resulting in greater storm intensities (Fadhel et al., 2018; Lenderink and van Meijgaard, 2008; Wasko and Sharma, 2015). Current literature shows that increased rainfall and more peaked temporal patterns of storms as a result of climate change will increase flood risk in urban areas (Fadhel et al., 2018; Hettiarachchi et al., 2018; Kundzewicz et al., 2014; Wasko and Sharma, 2015). In addition to storms increasing in intensity, climate change is also impacting the overall patterns of storm occurrences. The seasonal distribution of storm events are projected to change due to warming temperatures with 'wet areas getting wetter and dry areas getting dryer' (Marvel and Bonfils, 2013; Walsh and Lawler, 1981). Based on the Intergovernmental Panel on Climate Change (IPCC) 2014 report on climate extremes, the projected trends are for a higher proportion of the annual rainfall to occur in heavier rainfall events with some areas experiencing intense storm events even though total rainfall is projected to decrease (Seneviratne et al., 2012). Changes in the distribution of rainfall events over a longer period, such as the summer season, can impact antecedent conditions within the watershed (Ivancic and Shaw, 2015; Wasko et al., 2015; Woldemeskel and Sharma, 2016). Currently, literature investigating climate change impacts on urban

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flooding focus on single storm events of a particular return period, scaling Intensity-Duration-Frequency (IDF) curves with temperature or downscaling Global Circulation Models generated rainfall events (Arnbjerg-Nielsen et al., 2013; Fadhel et al., 2018; Guo and Adams, 1998; Hettiarachchi et al., 2018; Huang et al., 2016; Lambourne and Stephenson, 1987; Mamo, 2015; Nguyen et al., 2010; Sørup et al., 2016; Willems et al., 2012a; Zhou et al., 2016). While these studies show an increase in the threat of flooding in dense urban areas with high impervious surfaces due to climate change, they do not account for changes in rainfall distribution over extended periods of time. In short, they do not consider changes in Antecedent Moisture Conditions (AMC) for urban environments. If climatic change is expected to change not just rainfall intensities but the seasonal distribution of rainfall as well, it is only appropriate to look at storm events over a whole season.

There is little doubt that antecedent moisture impacts hydrologic modelling of large-scale catchments. Many studies have shown that AMC is a key factor in accurately modelling and predicting flooding in natural catchments (Ivancic and Shaw, 2015; Pathiraja et al., 2012; Sharma et al., 2018; Wasko and Sharma, 2017a; Woldemeskel and Sharma, 2016). In particular, Wasko and Sharma, (2017b) discuss the differences between the increase in rainfall intensities and the overall decrease in stream flows in a warming climate. They suggest that the 'lack of correspondence between precipitation and stream flow scaling' can be explained by changing temperatures causing changes in soil moisture and such factors, in effect, the antecedent conditions related to 'losses' from runoff rate and volume. Similarly, there are studies that have evaluated the effectiveness of green infrastructure and low impact development methods in mitigating flooding impacts (discussed in following section). But, as far as the authors are aware, there are few, if no studies that consider changes in AMC due to climate change and the impact on urban flooding. The lack of studies or urban catchments and initial conditions is understandable as the prevailing thought is that urban catchments consist of mostly impervious landuse types and are essentially "impervious" to variations in AMC. This is despite the increased use of green infrastructure as part of the tools that are used in adaptation to climate change impacts (Gill et al., 2007) and as retrofits to deal with existing flooding problems in cities. This green infrastructure approach leads to storage elements forming a larger part of urban stormwater management system as discussed in the following sections. Hence, the Initial Conditions (ICs) of these storage elements in smaller urban/developed catchments essentially become the antecedent condition similar to soil moisture deficit levels in a large-scale catchment. Therefore, we postulate that the current trend in adaptation methods and stormwater management in urban areas can increase the effects of AMC/IC on urban flooding. We speculate that if climate change results in changes to the distribution of rainfall events in a season, the impact on AMCs and ICs can actually modulate flood risk during more frequent storms, even though the more extreme storm events continue to result in severe flooding.

In Hettiarachchi et al. (2018) rainfall patterns during storm events adjusted to account for warming temperatures coupled with a detailed hydrologic and hydraulic model of a developed urban area showed that the intensification of rainfall due to climate change can increase urban flooding by as much as 35%. In this paper, we look at the seasonal distribution of rainfall over the summer period to determine the probability of flooding and how the frequency of flooding compares between warmer and colder summers. We use the mean summer period temperature to determine warm and cold years and use continuous simulation with a detailed H/H model to generate the resulting depth of water during rain events in a developed environment. We compare the model results for the warm and cold summers as proxy to discuss the impacts of a warming climate.

2. Urban stormwater management trends and relevance of antecedent moisture conditions

The world's urban population is expected to grow by 2.3 billion to 6.3 billion people by 2050 (United Nations 2011). This growth adds severe strains on urban cities for liveable space and infrastructure (Zhou, 2014). As cities expand and impervious land cover increases, even less severe (more frequent) storms can result in dangerous flood conditions. The added connectivity of surface runoff and storm sewer systems resulting from expanding urban areas also serves to compound this effect (Miller and Hutchins, 2017). Rainfall events that might have resulted in 'minor or nuisance flooding' can become 'major flooding' causing significant disruptions, danger to public safety and adding to the already significant economic impacts (Doocy et al., 2013; Moftakhari et al., 2017). Adapting to climate change impacts and flood mitigation, collectively referred as management of surface runoff in urban developed environments, has become a life critical factor as well as a severe challenge.

Urbanization can also impact catchment response to storms with increase in flow rates and decreasing water quality (Galster et al., 2006; Hollis, 1975; Nelson et al., 2006). These changes in flow rates and water quality tends to have a deleterious effect on the receiving water bodies such as stream, rivers and lakes (Barbosa et al., 2012). Degradation of water quality in surface water bodies leads to water contact and supply concerns that can also threaten human health (Gaffield et al., 2003; Sidhu et al., 2012). To curb such adverse downstream impacts due to changes or increases in impervious land area, stormwater management rules have been brought about by governmental and regulatory units such as city governments, catchment management organizations and basin management authorities. To that end green infrastructure, Low Impact Development (LID) methods, Water Sensitive Urban Design (WSUD), or Stormwater Best Management Practices (SW-BMPs) are common terms that are used to reference technologies and approaches that are increasingly used to address stormwater management in developed environments (Bertilsson et al.; Hancock et al., 2010; Kuller et al., 2017; Locatelli et al., 2017; McGrane, 2016). The authors will use SW-BMPs to reference all constructed stormwater management features for the remainder of this manuscript.

Some of the more common methods used to meet these requirements and mitigate flow rates and volumes include the use of detention/retention ponds, along with infiltration methods such as rainwater gardens, infiltration swales, green roofs, and subsurface storage (Pyke et al., 2011). Of these methods, retention/detention ponds are more widely used, especially in the USA, due to design and construction simplicity and relative effectiveness (Hancock et al., 2010; Semadeni-Davies et al., 2008). The current trend is to integrate these stormwater management features into the overall layout of the development plans (Fryd et al., 2010; Geldof and Stahre, 2005), as presented in Fig. 1. Housing developments most often use the stormwater management pond as a local amenity or as an avenue to provide for a natural ecosystem such as wetlands (Fig. 1).

The functionality of these SW-BMPs is dependent either on storing or infiltrating surface runoff generated during a storm event. The addition of such SW-BMPs makes AMCs relevant to the urban environment when looking at modelling these catchments. Along with the intensity, the temporal distribution of precipitation during a storm event can have a significant impact on the effectiveness these SW-BMPs (Hettiarachchi et al., 2018). AMCs will dictate how saturated or dry the soils are in infiltration based methods and will also determine the variation of water levels in detention ponds. The level of water in these ponds will determine the volume of storage available to mitigate excess runoff during a storm. This is why, contrary to the prevailing thought, modern day urban stormwater systems are not completely "impervious" to AMCs. Even though there are minimal to no natural streams or channels in majority of stormwater conveyance system in urban or development environments, these constructed SW-BMPs makes

Fig. 1. Examples of SW_BMPs (WSUD) incorporated in the urban landscape. (a) A storage feature in a park, (b) SW-BMP incorporated into a urban residential area (c) Stormwater pond as a local amenity in a suburban residential area, (d) a stormwater pond in an industrial area (Outdoor Design, 2018).

knowing the water levels prior to a storm event relevant to urban flooding and as a result, any changes to AMCs with climate change need to be considered in future urban flooding assessments.

3. Catchment model and data

The hydraulic component of modelling urban stormwater systems tends to be more important relative to large catchments and riverine systems where the hydrology dominates. Hence urban stormwater models require a higher level of detail to generate reliable and accurate flood results (Schmitt et al., 2004; Schreider et al., 2000). The depth of flooding, rather than the flow rate, becomes a key result in the context of urban flooding due to the complex hydraulic interactions with the built environment which cannot be adequately captured in rainfall-runoff models. For these reasons the Storm Water Model Management (SWMM) modelling package by the United States Environmental Protection Agency is used here. Among the various methods available in the Hydrologic/Hydraulic (H/H) modelling space ranging from the simple rationale method (Hromadka, 1989) to the very complex use or neural networks (Wu and Chau, 2011), the SWMM engine is widely used (Bisht et al., 2016) and forms the backbone of most of the dynamic H/H modelling packages used in the water resources industry.

The H/H model used here is based on a complex urban catchment in Minnesota, USA. This model was developed for the South Washington Watershed District (SWWD) in the State of Minnesota, USA to manage surface water flows as well as for planning and management of on-going development work and capital improvement projects. The catchment area of the SWWD is a highly developed urban/suburban area and extends over 65 M^2 ($\sim$165 km^2). The model was initially built in the year 2000 and has been continuously maintained and updated with the latest available landuse/land cover and stormwater infrastructure information. The model includes extensive detail of all landuse types and stormwater infrastructures including sewers, culvert crossing, open channel reaches, and constructed and natural storages. Highly detailed delineation of both sub-catchment boundaries and impervious area was done using a high resolution Digital Elevation Model (DEM), development construction and grading plan overlays, and aerial imagery within a Geographic Information System (GIS) environment. All surface runoff is fed into the appropriate inflow points of the hydraulic conveyance system. The model has been validated and used to design major capital improvement and flood mitigation projects (Hettiarachchi et al., 2012). The supplemental information associated with this paper includes detailed information on the model. The model includes geometry details to explicitly model the street overflow routes where flooding occurs as well as depth/area curves that capture flooding at the storage nodes. The detailed geometry included in the model provides an accurate representation of flood extents. For the purposes of this study and to reduce the complexity and model run times, the model was trimmed to the upper section of the SWWD representing an area of approximately 8.5 square miles (Fig. 2). It should be noted that the section of the model selected includes the most developed part of the overall watershed with a mix of high to low density residential, commercial and industrial type landuses. Therefore, this model can be assumed to represent a typical developed watershed and the results to reflect responses of typical stormwater systems in typical developed areas.

Precipitation and temperature data used in the analysis were sourced from the National Centers for Environmental Information hosted by the National Oceanic and Atmospheric Administration (NOAA). Both hourly and daily rainfall data were obtained from the climate data online site for Minneapolis and St Paul (MSP) International Airport gauge, which is the closest major airport to the study area. Daily data for the MSP airport was available from 1901 through 2014, while hourly data was available from 1948 through 2014. Though daily data is available through NOAA for more recent years, the modelling period was limited to 2014 due to the hourly dataset that ends that year. Daily maximum, minimum and average temperature data was also obtained for the period from 1901 through 2014. For this analysis, days that did

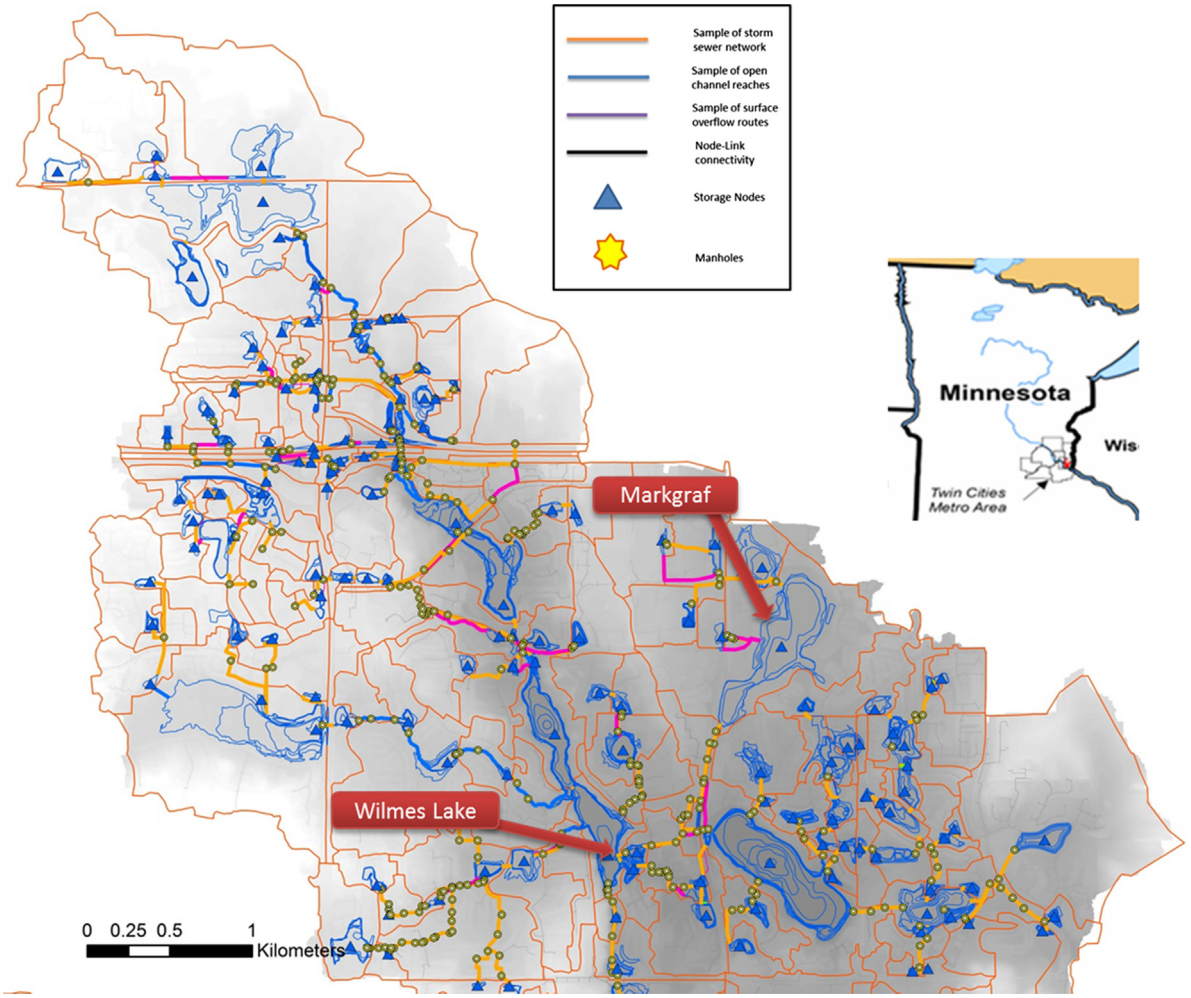

Fig. 2. Watershed areas with sub-watershed divides and model layout along with open water bodies and local stormwater management features. All open water bodies are shown as storage nodes. Also shows the two reference locations discussed in this paper. Wilmes Lake is the flow concentration point at the bottom, along the main draw of the watershed.

not have precipitation data were assumed to have no rain. The average monthly evaporation data for the same period as the temperature data was taken from the Minnesota Department of Natural Resources (MNDNR) climate data (available at https://www.dnr.state.mn.us/climate/wxsta/pan-evaporation.html). The daily average evaporation for each month during the summer period was added to the model based on the data available through the MNDNR and was unchanged for all model runs. Therefore, modelled results that are discussed are primarily dependent on changes in precipitation patterns.

4. Methodology

The workflow as described below follows three main phases. The overall approach is summarized in Table 1. Step 1 is the model setup so that it can accurately model extended periods in continuous simulation mode, which was followed by selecting the warm and cold years from the available historical data.

For this paper, we extract the modelled water levels at Markgraf and Wilmes Lake (Fig. 2). Markgraf is a local waterbody that drains a predominantly industrial watershed and used as a second reference location to present results. Wilmes Lake is a local minor lake along the main thalweg and the outlet point for this catchment as is the primary reference point for the model results. Availability of surveyed bathymetric data at these locations make them more suitable than most of the other open water bodies modelled, especially when water levels draw below the normal water level.

Table 1
Summary of workflow.

	Main phase	Steps completed
1	Model setup for Continuous Simulation	• Select summer growing season based on ice in/out months in Minnesota (May - Oct). • Validate model performance with available depth gauge data for Wilmes Lake for three separate years with a wide rainfall range.
2	Select Warm and Cold years	• Determine the average temperature for the summer season for each year. • Rank the years from highest to lowest average summer temperature and then select the 10 warmest years and the 10 coldest years (listed in Table 2).
3	Model Executions and Analysis	• Execute the model for the 10 warmest and 10 coldest years using hourly rainfall data. • Extract local maxima from depth results at Wilmes Lake and Markgraf. • Compare probability distributions for the precipitation with the maxima depth results at Wilmes Lake and Markgraf.

4.1. Model setup and verification

As the model used in this analysis has been continuously updated, verified, and extensively used for design of large-scale capital stormwater projects for over 15 years, the model verification process for this paper was limited to comparing the model performance when run continuously for the summer months. Johnson and Stefan (2006) discuss the variation of ice out months in the Minnesota lakes as it relates to the warming climate which indicates that the ice out dates have occurred earlier in the recent past. Their research shows that typical ice out for the southern part of the state is March/April. Hence the model start month was set for May to ensure that the water levels in open water bodies stabilize after the snow melt period and the starting water levels were set as the normal water level (NWL) or equal to the primary outlet elevation at all open water bodies. This would also ensure that any flooding caused by spring runoff would not be included in the results. The model end date was set at September to avoid the pre winter drawdown which occurs in October, where the lake level is artificially lowered to allow additional storage for possible excess snowmelt in the following spring.

By modelling for the entire summer seasons the H/H model essentially run as a continuous simulation (CS). This is not typically the case in H/H model analysis which are used for event based modelling, but studies exist that discuss and compare event based modelling with continues simulation for flood predictions. In particular Stephens et al. (2018) compares how event based modelling compares with continuous simulation based modelling in the context of impacts of climate change on flooding with both methods found to be appropriate. Avellaneda et al. (2017) uses EPA-SWMM, which is the modelling package used in this manuscript to look at cumulative performance of green infrastructure through long term simulation of these methods, which again supports the use of EPA-SWMM as an appropriate tool for this study.

As per the SWMM manual (EPA, 2016), the soil infiltration parameters were set at the driest level for the soil type, which essentially sets the maximum infiltration rate for a soil type at the start of the simulation. Typically, in event simulation, soil moisture parameters are set to an appropriate value for each soil type, but in CS the model continuously accounts for soil moisture and recharge of infiltration capacity during the simulation period which then correctly accounts for AMCs during a precipitation event. As discussed before, average monthly evaporation available from the State of Minnesota department of natural resources were used to update the model evaporation. For this study, the evaporation rates were set as daily values averaged for each month. To verify that the model setup was adequate to run continuously, the model was run for 3 summer periods that reflect wet, average, and dry years based on total summer rain. As shown in Fig. 3, results for these three verification years match reasonably well when compared to the available gauge lake elevations, confirming that the model can be applied for continuous simulation in this catchment.

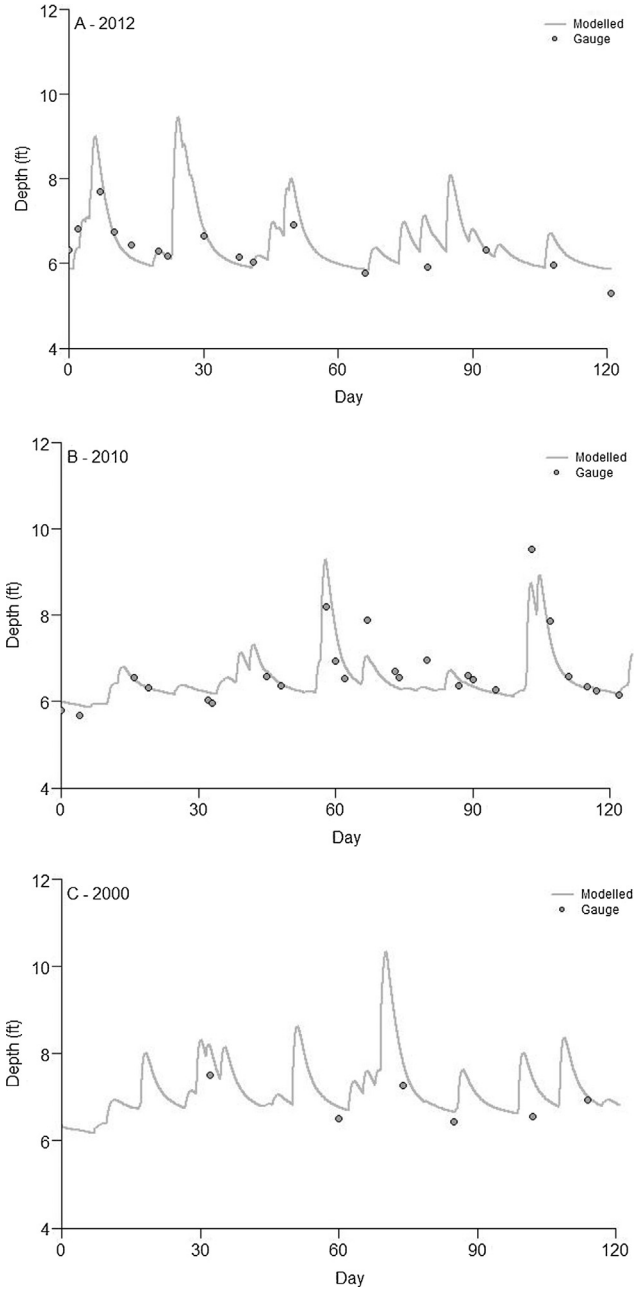

Fig. 3. Model lake level compared to available Wilmes Lake level gauge data (a) average total summer rain year – 2012, (b) wet or higher total summer rain year – 2010, and (c) dry or low total summer rain year – 2008.

4.2. Selection of modelled years

Daily temperatures for the summer months from 1948 through to 2013 were used to calculate the average temperature for the summer for each year to match the availability of hourly rainfall data used in the modelling process. The years were ranked from the highest summer temperature to the lowest summer temperature from which the ten warmest years were picked from the ten top ranked years and the ten coldest years were picked as the lowest ranked ten years. The selected warm and cold years are presented in Table 2 along with the average summer temperature for each year. It is interesting to note that the difference between the average of the warmest and coldest year temperatures is approximately 3 deg C, which corresponds to the predicted global temperature increase in the IPCC report on long term climate change projections by the year 2100 (Collins et al., 2013). These ten warm and ten cold selected years form the basis for the modelling analysis that follows which also helps to keep the level of modelling effort within reason. Selection of the summer period was intended to avoid periods of snowfall and focus the modelling analysis on flooding due to summer storms. Mass curves of daily rainfall for the summer period were generated for each of the 20 selected years. Using data extending back to 1948 is purely to represent rainfall patterns that have occurred along with the associated with the temperatures of each year.

4.3. Modelling and analysis

For each of the 20 selected years, the model was run from the 1st of May through the 30th of September with hourly rainfall spanning the modelled months distributed evenly over the watershed. After which the water level output from the model at Wilmes Lake and Markgraf were extracted for further analysis. The local maxima were identified

Table 2
List of the 10 warmest and coldest years based on average summer temperature in Minneapolis MN, USA.

10 Warmest Years	Temperature (deg C).	10 Coldest years	Temperature (deg C).
1953	18.8	1951	16.7
1955	19.3	1962	16.4
1988	19.1	1965	16.3
2005	19.0	1967	15.6
2007	19.6	1968	16.9
2010	19.0	1972	16.2
2011	19.1	1974	16.4
2012	19.2	1981	16.5
2013	18.6	1992	16.0
2016	19.3	1993	15.9
Average	*19.1*		*16.3*

from the continuous depth data generated from the model. Also, a set of local minima was extracted by setting a threshold equal to the elevation of the primary outlet that would then represent the occurrence of a minimum elevation in lake level at or below the hydraulic outlet elevation at Wilmes Lake. The distinction of minima below the outlet elevation of the lake is that this would represent low water surface elevations that occurred due to environmental forcing rather than hydraulic draw down of water level through outflow from the outlet. Probability Density Functions (PDFs) and empirical Cumulative Distribution Functions (CDFs) were calculated for the two sets of maxima points for the warm and cold years. Similarly, CDFs were developed for the peak rainfall intensities for the warm years and cold years along with CDFs for the minima below the outlet threshold.

5. Results and discussion

Here we present the results addressing the question of how climate change might affect AMC/ICs in urban catchments and thereby impact catchment response and flooding. Even though we are using historic data, Table 2 shows close to a 3 deg C increase in the average summer temperature between the 10 coldest and 10 warmest years which is similar to projected temperature increases (Collins et al., 2013; Seneviratne et al., 2012; Trenberth, 2011). Hence, we suggest that it is reasonable to use the results as a proxy to evaluate impacts of climate change on AMC/ICs and urban flooding. In addition, the majority of the warm years appear to occur after the turn of the century while most of the colder years are in the 1960s, again suggesting that we are comparing the past colder conditions with possible future warmer conditions. Fig. 4 shows the mass curves separated for the 10 cold years and 10 warm years. There is a clear difference in the rainfall pattern throughout the summer between the cold years and the warm years.

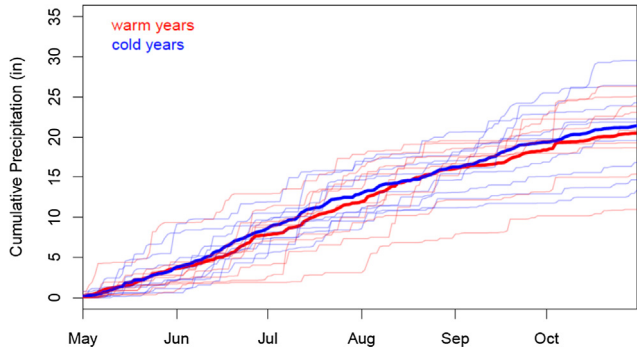

Fig. 4. Rainfall patterns during Spring Summer and autumn during the 10 warm and 10 cold years between 1948 and 2013. The darker lines represent a running average of rainfall through the season for the cold and warm years. (Refer to Table 2).

The variability is much greater for those years that classed as warm versus those that classed as cold. However, the average cumulative rainfall amounts, which are shown in thicker lines are similar. This suggests that although overall seasonal rainfall amounts are the same, the pattern, or intensities of individual rainfall events differs which is consistent with current available literature that projects rainfall patterns to change towards fewer, but larger more intense storms in a future warming climate. (Collins et al., 2013; Walsh et al., 2014). It is important to note that these rainfall patterns and temperature differences are based on historic data and not from weather generation of projected data using global circulation models of future climate change.

Following are the results presented in probability density function (PDF) and empirical cumulative distribution function (CDFs) curves which allows us to look at changes across severity and magnitude. Fig. 5(a) shows the PDF and Fig. 5(b) CDFs for the peak rainfall intensities that occurred during the set of 10 warmer years and 10 colder years. The PDF/CDFs for the warm and cold rainfall peak intensities show that the probability of more intense rainfall is higher during warm years, which is as expected and well documented in literature (Alexander, et al., 2006; Hettiarachchi et al., 2018; Lenderink and van Meijgaard, 2008; Wasko and Sharma, 2015). Though the mean intensities between warmer and colder years are not very different, the warmer years show a positive skew with more events exceeding a 2in/hr intensity. Fig. 5(a) shows that the rainfall in colder years occurs more frequently in events less than 1-inch/hour. Fig. 5(b) shows that there is a higher probability of rainfall intensities above the 20th percentile in the warmer years. Fig. 5 (a) and (b) confirm the qualitative assessment of Fig. 4 that the rainfall occurs in fewer more intense events in the warmer years.

The distribution of peak flood depths as a result of the modelling analysis is presented in Fig. 6. Fig. 6a compares the PDF of the peak depths, or the local maxima, at Wilmes Lake between the 10 warmest and 10 coldest years while Fig. 6(b) shows the CDFs of the same peak flood depths. Similarly Fig. 7 shows the CDF for peak depths at Markgraf. Comparing Figs. 5(a) and 6(a), there is a higher chance of a larger peak depth occurring in colder years. If, for the sake of comparison, we consider a flood depth of 8-ft for Wilmes lake, which is close to 2-ft above the normal water level, there is a higher frequency of flooding occurring in colder years than in warmer years, similar to Fig. 6(b) which shows that the probability of flooding, particularly at or below the 80th percentile, is higher in the colder years. Fig. 7 also shows a similar distribution at Markgraf where the warmer years are in the lower side of peak depths to approximately the 80th percentile. Even though the difference between warmer/colder flood peaks is smaller at Markgraf, due to the smaller watershed area draining to this storage area (only 0.4 M^2) this confirms the pattern of peak depth distribution at Wilmes Lake. Overall these distributions suggest that there is a higher probability of flooding in colder years. We note that the higher percentile rainfall intensities and peak depth do match in Figs. 5(b), 6(b) and 7, which shows that the extremely intense storms which have a higher occurrence in warmer years are most likely producing the highest peak depths.

These results essentially means there is a reversal between the distributions of peak rainfall intensities and resulting peak flood depths. This 'flip' between rainfall intensity and peak flood depths is clearer in the CDF plots in Figs. 5(b) and 6(b). This is an unexpected result as the conventional wisdom is that a higher frequency in intense storms is normally expected to generate a higher frequency of flood depths particularly in developed/urban areas. The p-value for a Kolgmorov-Smirov test, which is a non-parametric test for the difference between two samples, for a difference in the peak depths CDFs at Wilmes Lake is 0.041. The p-value suggests that the difference is statistically significant and not purely observed by chance. We also note that these results are based on historic data for the past 75 years. The rainfall patterns and temperatures used for this study are not based on any projections to the future using weather generators or Global Circulation Models. As

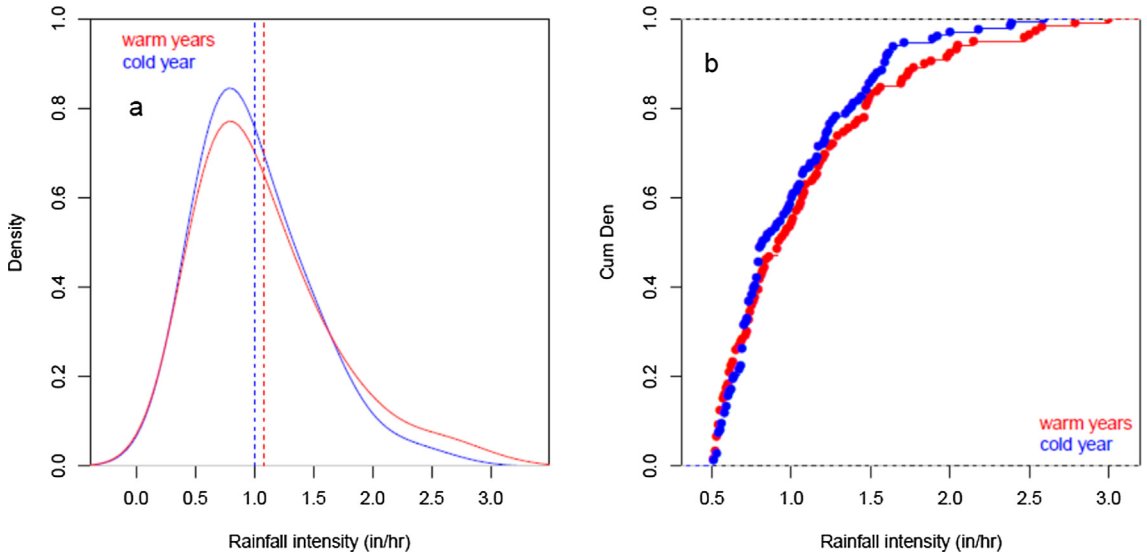

Fig. 5. Rainfall intensities for ten warmest and ten coldest years (a) probability density function (b) cumulative distribution function. The dashed lines in (a) are the mean rainfall intensity for the warm years (red) and cold years (blue), (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

discussed in the methodology, we used a simple approach of selecting the warmest and coldest years based on average temperature during the summer months from 1948, using the warm-cold year difference as a proxy for a future climate. Hence, the results present an indication on how rainfall patterns and the resulting potential for flooding can vary with temperatures as well as aiding our understanding of possible changes in warming climate.

To understand the 'flip' in the CDF between the intensity of rainfall and the flood peaks presented in Figs. 5b and 6b, distributions of the water level minima are presented in Fig. 8. Similar to the maxima, Fig. 8(a) shows the PDF and 8(b) shows the CDF of the minima below the outlet threshold. Fig. 8(a) shows that the water level decreased below the outlet level more often in the warmer years, especially between 5.5 and 6 -ft. Fig. 8(b) shows that there is a much higher probability of lower water elevations for the warmer years (compared to the colder years). This result shows that draw down of the lake due to environmental forcing occurred more often in the warmer years. Hence, there is a higher probability of water level being lower prior to a storm event during warmer years. The lower water levels means there is more available storage volume at Wilmes Lake. Therefore, the available storage to absorb the increased runoff during storms tends to modulate the impact of the higher intensity storms during warmer years. When the water level is higher than the outlet level, the rate of outflow or the drawdown of the water level after a storm is predominantly governed by hydraulic factors. Once the water level decreases to match the lowest outlet level from a storage pond or lake, there is no more flow through the outlet and any further decrease in water level is due to environmental factors such as evaporation. Hence the results presented in Fig. 8 demonstrate that pattern of stronger, but less frequent rainfall events during the summers of the warmer years allows evaporation from the lake to draw down the water level below the outlet level more often compared to the colder years.

The absolute values of flood depths difference between the warmer and colder years might not translate to an appreciable difference in

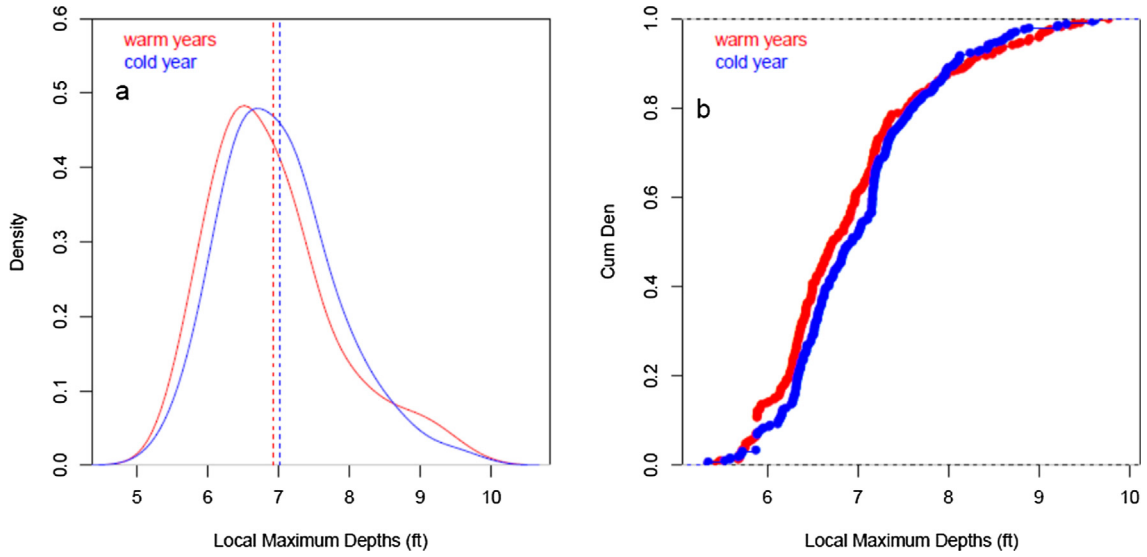

Fig. 6. Peak flood depths for ten warmest and ten coldest years at Wilmes Lake (a) probability density function (b) cumulative distribution function. Ref to Fig. 2 for location of Wilmes Lake. The dashed lines in (a) are the mean of the local maximum depths for the warm years (red) and cold years (blue), (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

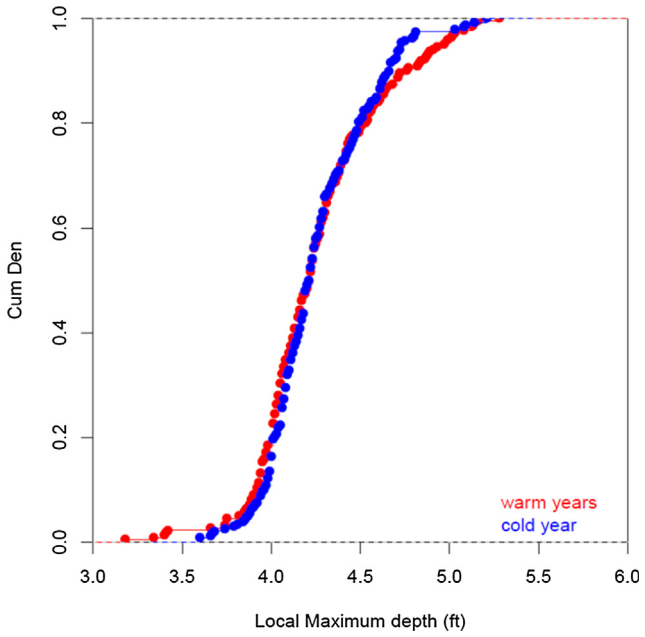

Fig. 7. Cumulative distribution function of peak flood depths for ten warmest and ten coldest years at Markgraf. Refer to Fig. 2 for location of Markgraf.

flood impacts and damages in this catchment depending on the frequency (return period) of the event considered. Nevertheless, the trend in the results is of great interest. The results presented here follow a similar pattern to those presented in Wasko and Sharma (2017b) where, for natural catchments, the change in stream flow did not generally correspond with the increase in rainfall during warmer years due to impacts of AMCs. The results discussed here show that AMC/IC can be an important factor in urban flooding as well.

The overall values of the difference in flood depths should also be considered in the context that these results are based on historic rainfall data and is not based on projecting to future climates. When considering global warming projections for RCP4.5 or RCP8.5, the changes in temperature and precipitation patterns could be more significant. The temperature difference presented here is not necessarily at the upper end of the projections, particularly over the land were we observe increases up to 6 °C. The potential for a greater modulation of flooding in urban areas due to changes in rainfall patterns and antecedent/initial conditions as a result of a warmer climate remains. Even though not specifically addressed in this manuscript, the effects of higher evaporation in a warmer climate can significantly add to this effect. It is important to also note that Fig. 5 does not change the probability of flooding at the extremes during the warmer years. As expected, extreme storm events will overwhelm the stormwater conveyance and management systems and will typically results in the highest level of flooding (Hettiarachchi et al., 2018).

5.1. How do the results explain the impact of AMC on urban flooding?

At the outset, we postulated that the increasing use of stormwater management features such as storage ponds and infiltration swales increase the impact of AMC on flooding even in urban developed environments. The results and discussion presented above substantiate this and support the hypothesis that changes in rainfall patterns coupled with changes in AMCs that can occur due to warmer temperatures can actually have a modulating effect on flooding. It is important to note that this effect is driven by different aspects of AMCs between larger rural catchments vs. urban and developed areas. The prevailing idea of how AMCs impact runoff rate and volume from catchments focuses primarily on how much soil moisture is available and the resultant abstraction of rainfall. What this study shows is that in the case of urban catchments, it is the initial conditions in stormwater management features that impact AMC conditions that result in abstraction of runoff volumes and the effect on flood levels, and this is true for even the smallest of urban catchments. As discussed before, abstraction due to soil moisture deficit can be considered equivalent to 'hydraulic abstraction' in urban catchments. One important consideration is that AMC and the level of 'hydraulic abstraction' is effective and relevant mainly in urban catchments with distributed stormwater management features. With that said it is also important to note that use of distributed stormwater management in developed areas is the current trend and will be a common feature in built environments as adaptation to climate change continues.

5.2. Implications on urban flood management

The potential modulating effect that we discussed in the paper can

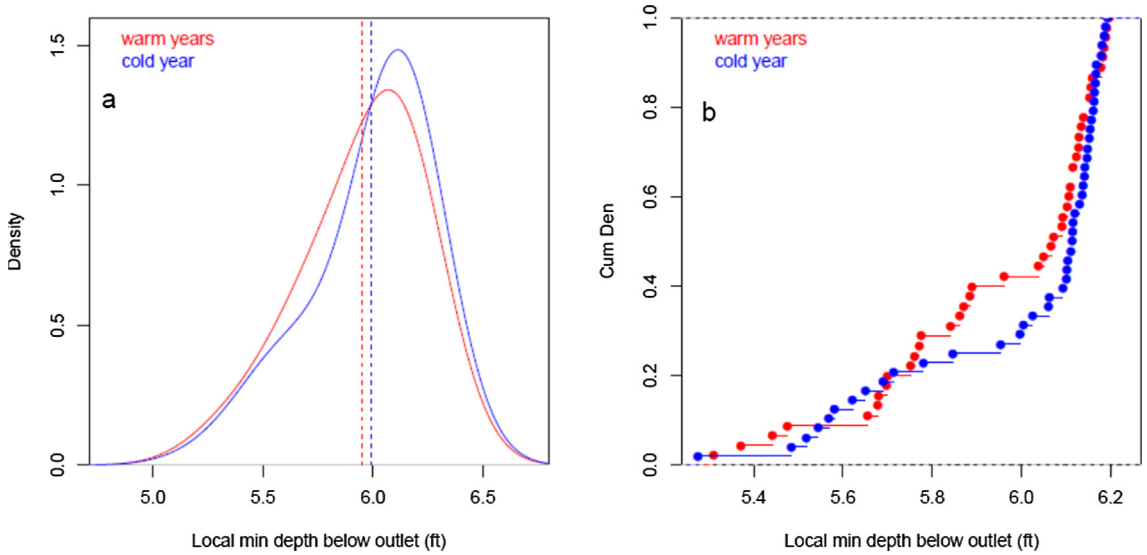

Fig. 8. Minimum depths below the outlet at Wilmes Lake (a) probability density function (b) cumulative distribution function. Ref to Fig. 2 for location of Wilmes Lake. The dashed lines in (a) are the mean of the local minimum depth for warm years (red) and cold years (blue), (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

have a significant impact on the design of SW-BMPs. The broader range of results that are generated from the modelling approach in the study can lead to a more cost effective design of SW-BMPs and can increase the probability that these management features will provide the intended benefits to the catchment over a wider range of naturally climate conditions. When considering the severe economic impacts of flooding with the cost of global flooding exceeding multiple billion dollars a year (EM-DAT) and is expected to get worse in the future (Doocy et al., 2013), this approach can also increase potential to optimize benefit/cost ratio as well as make better use of the limited space available in urban/developed environments for SW-BMPs. Other studies that have looked at design of urban stormwater systems and adaption methods within the uncertainties of climate change also present the need to adopt a flexible design approach (Arnbjerg-Nielsen et al., 2013; Refsgaard et al., 2013).

This study further illustrates the need either (a) move away from single event based modelling and analysis in preference of continuous simulation, or (b) develop methods to adequately consider changes in AMC in event based modelling even when modelling developed urban catchments. The discussion above results from the fact that the modelling analysis was done over the entire summer period for each year using continuous simulation. This allowed the system to emulate the natural processes that occur in the catchment to a sufficient level to capture the variability in flooding that occurs over a longer period. The current technology and available data allow this type of analysis to be done without too much additional effort and the added value in correctly describing flood response as a function of AMC far outweigh the expended effort and costs. The uncertainties in H/H modelling and the variability of climatic drivers related to flooding are well documented (Beven and Binley, 1992; Franz and Hogue, 2011; Renard et al., 2010). Modelling longer periods using continuous simulation can help mitigate some of these uncertainties when trying to characterise stormwater systems using mathematical equations when modelling urban catchments.

As previously discussed in this paper, AMCs have been shown to have a significant impact on runoff generated from large catchment areas where it generally accepted in hydrology that, a certain return interval storm does not always generate the same return interval runoff, and nor does it always result in the same return interval flood depth. As for urban catchments, this disconnect has been largely ignored, mainly due to the nature of high percentage of impervious land cover which lends to assume that a certain IDF storm would generate the same return interval runoff, and thereby the same return interval flood depths. What we have shown in this paper is that this assumption might not always hold true even in urban catchments and developed areas. With new SW-BMPs that are more common in development projects and as retrofits for flood management, there can be a similar disconnect between the return interval of a storm and the flood depths, albeit the surface runoff generated might still be the same. We have shown that there is potential for SW-BMPs to be more effective in future warmer climates and create a disconnect between the intensity of storms and resulting floods. All of the above point to the fact that a wider range of simulation of stormwater systems and looking at longer periods of analysis will assist in better designs and better choices on adaptation, and will increase the resiliency of the system to combat the impacts of climate change in urban environments.

6. Conclusions

In this manuscript, we performed long term (continuous) modelling of an urban developed catchment to evaluate the impacts of changing distribution of precipitation events in a changing climate. By coupling changes in storm rainfall intensities and seasonal rainfall patterns we show that both are equally important to the flood response in a future warmer climate. We also show that antecedent conditions can and do impact flooding in current developed urban environments that include constructed stormwater management features, which is in contrast to prevailing thought and literature. We argue that these urban stormwater management features can behave in a similar way to soil moisture deficit in large-scale natural catchments. Even though the probability of higher rainfall intensities increased during warmer summers, the probability of flooding during warmer years reduced. Although widespread flooding can be expected resulting from the most rare and extreme storms, the results here suggest that the inclusion of the variability of AMC/ICs that can prevail in a future climate along with projected distributions of rainfall events can have a modulating effect on flooding in many current constructed environments.

The methods used for this study are simple and straight forward and can be applied to almost any urban area with a stormwater system model with sufficient detail. The implications of doing a similar analysis can be significant when looking at design of flood mitigation and adaptation methods in urban, developed environments. The generation of a probability distribution of results can help with a risk based optimization for adaptation and a more flexible design approach to take maximum advantage of limited space in urban areas and provide a more resilient level of flood protection for prevention of loss of life.

The authors see two elements that can further improve this study. The first is to apply this analysis to different watersheds and in different climatic regions although we acknowledge that the availability of models with sufficient detail to repeat this analysis in other areas can be a challenge. The second is to add a more detailed accounting for evaporation. A daily temperature based modelling of evaporation will add to a better response in open water bodies to temperature variation, especially when considering that the temperatures are expected to increase in a future climate.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.01.039.

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